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PROTON RECOIL MEASUREMENTS OF THE PuBe SOURCE NEUTRON SPECTRA

by R. L. Alexander, D. F. Shook, and C. H. Ford
Lewis Research Center
Cleveland, Ohio

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ABSTRACT

The spectrum of a 5 Ci PuBe neutron source has been measured from 40 keV to 800 keV. The measurement was made using a spherical proportional counter containing 4 atmospheres of hydrogen. Pulses due to gamma-ray interactions in the chamber were distinguished by rise time analysis using a two-parameter pulse-height analyzer. The proton recoil spectrum was analyzed using a code written by Benjamin which accounts for contributions to the proton recoil spectrum from neutrons of energy greater than that to be analyzed.

The proportional counter measurement is combined with a recent liquid scintillator measurement to give a complete spectrum. Good agreement exists between the two measurements in the region of overlap from 500 to 800 keV. The proportional counter data show that the flux is fairly smooth and flat in the region from 40 keV to 800 keV.

The present measurements indicate a neutron yield below 1 MeV for this source of 20.2 $\pm$ 3.9 percent.

E-6133

INTRODUCTION

For many applications of radioactive neutron sources it is necessary to have an accurate knowledge of the neutron spectrum as well as the source strength. The use of large water bath techniques has made it possible to determine source strengths to an accuracy of 3 percent or better but the neutron spectrum is not nearly so well known. Considerable past work with emulsions and organic scintillators has resulted in fairly well established spectra at energies greater than about 1 MeV but below this energy the spectra of many radioactive sources have not been measured.

In the present work a 5 Curie (Ci) PuBe source spectrum is measured from 800 keV down to 40 keV using a spherical proportional counter (1). This measurement is combined with a recent liquid scintillator measurement (2) to give a complete spectrum. The primary difficulties in making a proportional counter measurement of the low energy part of the Be(α,n) spectrum are caused by the large number of high energy neutrons emitted by these sources, and by the gamma-ray background.

EXPERIMENT

A spherical proportional counter designed by Benjamin et.al., (1) was used in the measurements. The counter was filled with 4 atmospheres of hydrogen and a trace of helium-3 and had an inside diameter of 3.94 cm. The counter wall was .051 cm thick stainless steel. A lead shield about .64 cm thick, and an outer cadmium cover about .075 cm thick surrounded the counter.

The measurements were made with the counter mounted on a light frame 1.8 meters above the floor of a room 4 meters high, and 6 meters square. The PuBe source was supported with its axis vertical at 15 cm from the counter by a .62 cm diameter threaded iron rod.

A block diagram of the electronics is shown in figure 1. To separate protons from electron recoils, a two-parameter analyzer was driven by an identification signal as well as by a linear signal. To preserve the linear response for large pulses in hydrogen, which may take up to 6 μ sec to rise, the preamplifier decay time was made 130 μ sec, and a single 7 μ sec RC integration and differentiation time constant was chosen in the linear amplifier. To obtain an identification pulse separating fast-rising proton recoils from electrons, the preamplifier output was R-C clipped with a short time constant in the second linear amplifier. This pulse was used to drive a fast stretcher and a slow stretcher of about 5 μ sec duration. The slow stretcher pulse was adjusted to reach its peak at its end. Finally, the identification pulse was delayed 4.75 μ sec. These precautions ensured that the two-parameter analyzer would always convert the full voltage of the linear signal.

Careful measurements were made of the analyzer linearity and pulse height zero. Amplifier gains were measured and absolute gas gains were obtained using the 764 keV helium-3 peak. A plot of ln A/V versus ln V gave a straight line over a range of gas gain from A=8 to A=250.

Measurements were made with gas gains of from 45 to 180. The resolution of the helium-3 peak was about 10 percent full width at half maximum (FWHM).

THE 5 CURIE PuBe SOURCE

This source is a right cylinder, outer diameter 3.33 cm, and length 6.91 cm. It contains 79.88 gms of plutonium and 39.30 gms of beryllium intimately mixed and melted in a tantalum cup and doubly encapsulated in stainless steel.

The source emission rate was 9.50 $\pm$ .29 neutrons per second in September of 1962. The isotopic fraction of plutonium-241 was .74 percent (3). This corresponds to an initial rate of increase of source strength due to the formation of americium-241 of 2.1 percent per year.

The source strength in September 1970 is estimated to be 13.6 percent greater than in 1962. The relative emission rate of this source as a function of direction was measured with a long counter, the center of the front fact of which was at 100 cm from the center of the source. The emission rate in the direction perpendicular to the source axis was measured to be 1.067 $\pm$ .020 times as great as the emission rate averaged over the total solid angle. The calculated neutron flux at one meter from the source perpendicular to the axis is then

$$\phi = \frac{9.50 \times 1.067 \times 1.136 \times 10^6}{4\pi\ (100)^2} = 91.6\ \text{n/cm}^2\text{sec}$$

DATA ANALYSIS

The maximum pulse size that can be produced by a gamma-ray in this chamber corresponds to that of about a 100 keV proton, so that there is no gamma-ray interference above this energy. Consequently, the proton recoil data analysis is straightforward. The Spec 4 code of Benjamin (4) was used. This code requires a neutron spectrum shape above the highest energy to be analyzed. The required shape was obtained from the data of reference 2. The code generates a proton recoil response shape for neutrons above the energy to be analyzed, using analytic response functions. It then normalizes this shape to the data, and strips the differentiated remainder.

Below about 100 keV proton energy, gamma events occur in the chamber. A two-dimensional plot of counts from a cobalt-60 source is shown in figure 2. The pulses from a 40 keV electron travel a total distance equivalent to the diameter of this chamber, and may require as long as 6 μ sec to rise. Consequently, at a given energy the clipping circuit places most of the pulses near the energy axis.

Figure 3 shows data from the PuBe source. A 100 keV proton in the counter travels only about a millimeter, so that all of the 100 keV proton pulses should rise within the clipping time of the identification circuit. These pulses appear as a peak in the identification channel. Since the identification pulse size for these pulses is proportional to the energy, this peak occurs in a diagonal line on the plot (5).

Unfortunately, not all the pulses on this plot can be clearly ascribed to the proton-recoil peak, or to gamma-rays. Above 100 keV, where the gamma-ray induced pulses are gone, there is a flat continuum of pulses which have smaller identification pulses than those in the peak. It is believed that these pulses are due to higher energy protons that lose only a fraction of their energy in the gas before colliding with the wall. At 2.5 MeV for example, a proton will lose 100 keV while travelling nearly 2 cm. in the gas.

Figure 4 shows the spectrum of pulses from the source surrounded by a spherical shell of tungsten, which sharply reduces the fraction of high-energy neutrons in the spectrum. The calculated fraction of the flux above 2 MeV in the tungsten leakage spectrum is only 17 percent compared with 70 percent for the bare source. The number of counts not on the diagonal have been much reduced. This non-peak fraction is 35 percent at 100 keV for the bare source, and only 4 percent for the tungsten leakage spectrum.

It is possible to subtract an arbitrary fraction of a gamma-ray spectrum from a mixed spectrum so as to obtain a smooth continuation below 100 keV of the distribution above 40 keV, so that the subtraction is from the non-peak counts.

Figure 5 shows the total counts measured for the 5 Ci PuBe source. Two slightly different gamma fractions are subtracted below 100 keV. The non-peak contribution to the spectrum for these subtractions is shown also. A modified version of Spec 4 was used to calculate the fraction of recoils from neutrons of energy greater than 1.5 MeV. This is also shown in figure 5. Figure 6 shows similar results for the tungsten leakage spectrum, where the non-peak fraction is much lower.

In both fluxes, the fraction of non-peak counts is not a constant with energy. For a fixed clipping time, there will be some energy of proton-recoil below which all the recoils will be in the group along the diagonal. The rise time for these very small pulses will be within the clipping time. Since the absolute number of recoils from high energy events increases only about 10 percent from 100 keV to 10 keV, the number of counts occurring off the diagonal should, at most, rise no more than this.

The uncertainty in the gamma-ray subtraction above 40 keV is of the order of the difference between the two subtractions shown in figures 5 and 6. The approximate upper limit of the counts in the non-peak fraction is the upper curve shown. If one subtracts more than enough to give the lower curve, portions of the identification channel region become negative.

RESULTS AND DISCUSSION

The solid line of figure 7 shows the neutron flux spectrum reduced to 1 meter distance for the 5 Ci PuBe source as presently measured by the 4 atmosphere hydrogen proportional counter. The curve drawn through the data is the weighted averages of two runs each above and below about 100 keV. The hatched area represents the estimated error. The analysis is not inconsistent with a nearly featureless spectrum. But the analyses of runs taken on different days show the source spectra features reproduced here. Below 70 keV, the large uncertainty in the spectrum is caused by the uncertainty in the gamma fraction subtracted from the non-peak data. Because the non-peak proton recoil contribution is expected to decrease with decreasing neutron energy, the upper limit of the spectrum shown is believed to be near the upper limit for the spectrum in this region. The lower limit is not so clearly defined.

The integral of the flux from 0 to 800 keV with a flat 30 n/cm^2 sec MeV below 40 keV is 15.6 ± 2.7 n/cm^2sec. The total flux at one meter is calculated to be 91.6 ± 3.7 n/cm^2sec. The data of reference 2, therefore, have been normalized to include 76.0 n/cm^2sec between 800 keV and 11 MeV. The fraction of the neutron spectrum below 1 MeV is then 20.2 ± 3.9 percent.

The spectrum of reference 2 is very similar to that of Anderson and Bond (6) who measured the spectrum of a similar PuBe source with nuclear emulsions. Their measured spectrum extrapolated smoothly to zero neutron energy indicated about 18 percent below 1 MeV. St. Romain, et.al., (7) using Bonner spheres to estimate neutron yields found about 17 percent of the spectrum of a 1 Ci PuBe source below 1 MeV. They inferred a peak in the neutron spectrum at 0.3 MeV due to inelastic scattering of alpha particles from beryllium. The excited beryllium nucleus was postulated to decay by neutron emission. Shook, et.al., (8) measured the age of neutrons in various media and using a similar 5 Ci PuBe source, estimated that 21 percent of the neutrons were emitted below 1 MeV. They used the Anderson and Bond spectrum above 1 MeV.

In conclusion, the neutron spectrum of a 5 Ci PuBe source measured from 40 keV to 800 keV is generally flat and smooth. The measurement indicates there are about 20.2 ± 3.9 percent of the neutrons emitted below 1 MeV, which is consistent with other measurements in magnitude but not in shape. The method of estimation of the contribution of gamma-rays to the recoil spectrum below neutron energies of 100 keV is the principal source of uncertainty in the present proton-recoil measurements which have large fractions of the proton recoils caused by high-energy neutrons.

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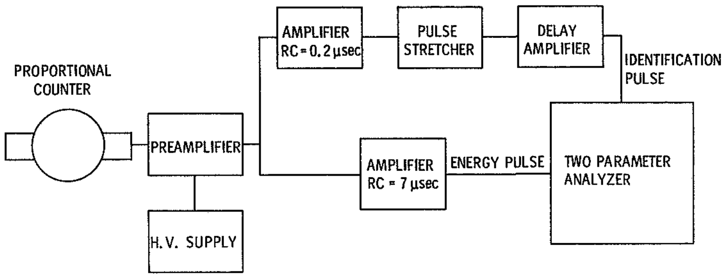

Figure 1. - Block diagram of instrumentation.

IDENTIFICATION PULSE HEIGHT

RECOIL ENERGY (keV)		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
	1	131C72																															
	2	185217																															
	3	181174																															
	4	85942	1																														
	5	48743	13																														
	6	336C6	149	5	1																												
	7	24248	495	48																													
	8	18533	795	196	14	1		1																									
	9	13715	889	331	63	6																											
	10	10824	965	425	125	17	5																										
	11	8425	993	44C	250	60	18	3																									
	12	6477	1040	538	256	95	32	2	1																								
	13	5195	1024	556	250	116	50	18	2																								
	14	4C53	1C07	585	33C	139	60	23	8																								
	15	3474	987	605	348	200	75	30	12	3	1																						
	16	2679	929	603	330	207	98	45	14	7	2	1																					
	17	2211	912	603	383	207	108	44	20	9	3	1																					
	18	175C	867	60C	344	250	117	59	27	5	2																						
	19	133C	801	609	37C	238	114	63	29	13	3	1																					
40	20	1C94	741	537	384	218	130	64	35	17	6	5	1																				
	21	758	664	526	329	209	128	82	24	21	11	1		2																			
	22	577	563	472	362	234	138	77	32	22	11	3	1	1																			
	23	4C4	511	448	340	192	141	76	44	25	5	6	1																				
	24	309	466	430	269	209	117	78	50	31	10	5	1																				
	25	234	334	371	326	198	124	74	38	25	11	5	2	1																			
	26	176	293	333	274	199	110	74	37	16	11	7	2	1																			
	27	91	222	236	224	191	127	65	41	21	11	8	4	1																			
	28	75	198	228	197	160	100	55	38	16	11	7	3																				
	29	55	152	196	169	132	106	58	24	18	9	4	1	1																			
	30	21	101	145	149	132	78	65	29	25	16	3	1		1																		
	31	18	75	143	152	114	74	51	35	17	11	3	4	3			1																
	32	1C	66	115	11C	110	75	44	27	19	7	5	5	1	2	1																	
	33	8	40	87	96	90	66	49	31	19	7	7	6	3	1	1																	
	34	1	28	63	68	80	60	41	21	9	9	5	3	2	1																		
	35	1	22	45	6C	65	54	39	22	10	9	4	1	1	1																		
	36		12	36	57	49	42	34	24	7	8	7	1		2	1																	
	37	1	10	24	40	29	38	17	16	15	8	4	3	1																			
	38	1	2	14	27	30	26	27	23	9	10	1	2	1																			
	39		4	12	14	21	25	23	7	11	7	5	2	2	2	2																	
	40			5	17	26	23	20	5	8	3	1	1	1																			
	41		2	4	15	9	13	20	8	15	5	5	1	1																			
	42			5	8	10	13	9	8	10	4	2	1	1																			
	43	1		3	6	12	5	8	3	8	4	1	1			1	1																
	44			1	6	9	10	6	8	6	1	6		2																			
	45			2	5	6	9	5	6	7	3	2	1			1		1															
	46				3	3	6	6	4	2	3		2	1			1																
	47					2	1	2	3	2	1	2	2	1			1	1															
	48				3	3	1	4	2	2	3	3	1																				
	49					1	5	4	2	2		3		1																			
	50					4	1	3	2	1	1																						
	51						1	1	3	1	2	2		1																			
100	52				2		2	1	2	2	2	1																					
	53					1	2	3	1	2			2			1																	
	54					2		2		1	1																						
	55									2			1																				
	56					1	1	1					1																				
	57							1	2		1	1	1																				
	58						1	1	1																								
	59							1				1	1		1																		
	60								1																								
	61																																
	62						1					1																					
	63																																
124	64												1																				

Figure 2. - Proportional counter data, cobalt-60 source.

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IDENTIFICATION PULSE HEIGHT

RECOIL ENERGY (keV)

keV	Row	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
	1	1C72																				
	2																					
	3																					
	4	40424	341	146	117	48	31	15	24	13	6	5	8	2	2	4	4	3	1	1	3	3
	5	164216	554	116	47	23	10	11	8	3	5	3			2			3	1	1		
	6	217442	4772	318	80	32	14	11	6	2	5			3	2			1	1			
	7	132982	6517	3008	169	61	29	10	8	1	8	4	1	2						1		
	8	92672	5167	4860	202C	99	37	19	9	8	6	2	5	2	3					1		1
	9	67596	5191	2658	4172	1345	78	36	10	12	8	2	2		1	2	2	1	1			
	10	50947	5254	2743	1895	3760	940	65	22	11	7	7	2	4	3	1	2		1	1		
	11	39619	5211	2650	1461	1802	3532	592	34	23	15	5	3	3	2		2	1	2			
	12	30927	5117	2854	1501	911	1966	3C42	358	31	17	11	7	5	3	3	4		1	1	1	
	13	24424	5002	2966	1631	926	712	2168	2558	230	24	16	7	2	5	3	2		1	1	1	1
	14	19428	4987	2899	1802	902	571	569	2301	2060	159	19	13	8	6	5	3		1			
	15	15049	4655	2972	1778	1073	573	398	608	2557	1663	87	25	16	9	9	5	1		2	1	1
	16	12216	4339	2989	1869	1054	613	362	328	756	2677	1256	78	23	14	4	3	7	2	2	4	1
	17	9759	4038	2994	1899	1159	620	367	260	275	910	2703	866	46	17	8	5	5	4	3	2	1
	18	7728	3864	2775	1856	1204	705	392	206	236	278	1131	2525	518	39	14	10	3	4	2	1	3
	19	6023	3529	2670	1853	1207	687	403	254	199	175	309	1447	2296	415	34	16	5	5	3	2	1
40	20	4688	3258	2658	1809	1167	786	448	271	213	155	183	354	1533	2008	285	22	9	7	5	6	1
	21	3451	2900	2394	1754	1233	669	448	271	202	154	148	183	552	1422	1550	131	22	18	4	3	3
	22	2717	2502	2221	1683	1101	687	458	278	186	138	102	116	180	622	2366	1330	93	18	15	5	3
	23	1985	2223	2023	1589	1120	694	455	280	179	108	112	115	144	189	742	2135	1046	62	21	18	6
	24	1472	1886	1798	1419	1059	698	445	304	193	142	108	90	106	126	205	850	2040	685	42	11	7
	25	993	1662	1673	1331	976	706	422	262	189	144	100	101	89	85	121	253	1056	1956	490	29	17
	26	713	1363	1433	1256	942	668	421	278	189	112	104	89	97	82	90	121	306	1189	1862	327	31
	27	502	1056	1344	1094	879	634	440	246	175	133	103	85	87	83	89	100	119	358	1318	1607	239
	28	295	833	1102	1030	829	560	371	243	189	131	103	81	68	75	81	77	110	135	489	1454	1296
	29	227	661	874	919	748	548	371	236	162	134	93	52	75	72	67	96	77	107	217	545	1541
	30	109	505	749	773	721	507	339	254	195	108	97	90	68	73	54	74	78	85	93	196	660
	31	64	391	663	672	616	450	321	243	162	118	93	87	82	58	67	49	42	72	69	72	274
	32	56	244	527	626	543	413	326	245	170	120	106	88	85	74	55	52	61	57	70	63	111
	33	36	208	372	568	515	389	265	217	154	115	98	88	59	63	68	49	45	60	56	62	75
	34	11	130	319	458	467	324	270	188	151	130	106	99	74	65	57	45	66	71	48	68	79
	35	11	81	228	369	372	333	268	192	155	122	105	81	65	57	50	49	50	47	47	43	59
	36	7	54	195	305	322	292	279	210	146	128	88	66	75	58	55	43	61	44	56	48	46
	37	6	24	128	251	282	269	226	197	140	115	111	78	57	53	72	38	54	45	55	44	53
	38	3	21	121	221	222	256	218	168	141	124	103	71	74	54	52	44	55	41	32	46	50
	39	3	17	93	141	217	231	222	181	157	107	103	91	67	53	49	56	53	39	42	53	44
	40	2	5	58	163	211	224	213	160	114	113	84	67	64	51	62	52	55	38	48	41	59
	41	2	4	47	118	188	168	171	164	134	109	95	73	88	58	46	46	55	46	42	46	47
	42	1	2	28	107	140	164	168	154	132	104	81	88	61	81	52	55	53	57	37	42	39
	43	2	5	15	73	132	155	163	117	123	107	84	66	66	68	60	51	52	47	32	48	44
	44	1	1	12	78	123	153	142	125	105	114	106	86	78	63	69	55	45	53	40	43	38
	45	3	1	10	47	110	141	138	121	120	92	100	75	58	73	56	50	53	31	45	32	29
	46	4	1	7	41	95	120	151	134	116	89	72	79	70	73	55	53	50	43	44	35	44
	47	3		4	26	76	105	142	132	129	86	86	77	83	62	61	43	48	35	37	51	37
	48	1		2	23	70	96	124	109	114	100	94	81	68	65	62	54	55	57	36	42	41
	49			1	17	54	109	129	108	96	100	88	79	80	68	50	51	76	48	50	32	41
	50	2	2	1	9	42	80	119	112	106	92	85	79	75	73	58	66	48	46	39	43	31
	51	1	2		9	37	71	93	104	127	109	104	69	70	67	54	59	50	51	26	52	45
100	52		1		6	26	76	95	124	119	95	80	83	65	80	66	55	45	46	44	47	42
	53	1		1	4	19	48	87	121	104	89	79	74	70	69	86	49	51	57	51	36	42
	54			1		17	44	76	104	118	82	84	74	57	64	55	65	53	53	51	50	38
	55		1		3	18	49	70	102	103	97	89	68	76	58	70	58	54	50	42	53	44
	56	3	1		1	7	30	63	83	94	119	87	80	89	83	66	57	54	55	41	37	40
	57	1			1	14	23	70	93	99	90	73	103	72	74	66	53	62	51	54	52	49
	58	1		1		5	32	59	95	87	82	83	85	72	55	68	70	52	53	49	48	35
	59	1				7	28	63	82	94	90	81	79	66	61	62	59	45	46	47	46	35
	60	2	2			2	25	52	67	70	69	71	98	59	59	74	57	66	48	32	42	46
	61	1			1	1	13	36	87	85	107	86	86	79	69	53	64	48	50	57	54	45
	62	1	1	1			13	44	66	95	100	83	71	74	63	64	50	44	40	41	54	48
	63	1				2	7	25	62	71	98	90	71	71	64	57	55	57	58	47	48	43
124	64	2			1		7	20	47	67	68	74	68	77	64	64	50	49	51	64	60	54

Row	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
1																					
2																					
3																					
4							1														
5					1									1		1					
6																					
7																					
8						1															
9					1			1													
10	1					1															
11	1			1					1												
12	2		2	2					1												
13		2			1								1								
14	1	1			1																
15			1	1								1									
16	1	2	1	2																	
17		2	1																		
18		2		2			1	1					1								
19			2	1					1			1			1						
20	6		1		1			1		1											
21		3			1		1	1	1			1		1							
22	2	2	5	4		1															
23	5	1	2	2		2	2	1	1		1										
24	6	1	2	3	1	1	1				1										
25	8	8	2	3	1		1	1				1	1								
26	12	8	5				4	1	2		1	1									
27	18	7	9	1	8	2	1			2	1							1			
28	129	23	15	6	3	3	1	2	4	2					1			1			
29	1131	103	15	9	9	1	1	6	1	1						1					
30	1598	918	70	18	7	8	4	1	3	1	5					1					
31	769	1639	671	41	14	12	5	2	2	1		1	2	2			1	1	1		
32	292	866	1558	480	32	16	10	6	3	1		2	1	2	1				1		
33	128	382	917	1457	374	27	14	4	5	3	3	1	1					1			
34	79	131	430	1085	1340	260	21	14	4	2		2	2	2	1	1	1	1			1
35	61	93	183	460	1147	1182	176	12	8	4	4	2	2	2			2				
36	45	65	88	220	536	1126	981	125	3	10	7	2	3	1		3	1			1	
37	50	52	70	118	258	622	1205	347	69	13	11	4	3	1	1	1					
38	43	45	57	67	122	271	660	1219	726	54	12	5	6	4	1	6	2			1	
39	24	38	48	65	74	165	319	589	1197	574	39	11	2	8	2	3		2	1	2	
40	32	46	34	44	63	86	164	326	741	1126	416	25	11	9	5	1		1	2		
41	37	39	34	57	47	60	114	175	403	744	1108	302	19	5	6	9	1	2		2	2
42	41	43	41	32	45	33	54	115	233	432	837	987	232	18	9	3	2	2	1	1	1
43	49	37	38	30	44	38	50	86	125	255	457	872	876	181	15	5	3	2	1	3	2
44	38	42	26	33	35	37	34	65	83	162	c40	552	844	738	117	11	6	2	3	1	1
45	42	41	31	34	32	31	37	37	51	93	170	298	554	813	65C	118	12	4	5	2	2
46	32	40	40	23	30	38	38	34	35	58	113	181	334	548	880	541	53	7	1	5	1
47	52	43	40	34	32	32	29	35	35	34	54	1C1	192	351	564	816	479	55	8	9	4
48	34	4C	28	34	22	28	25	30	40	29	67	75	123	229	402	546	792	434	51	9	4
49	38	43	33	20	33	31	26	31	32	19	39	65	94	147	222	341	592	788	343	40	6
50	28	35	32	32	30	35	24	23	35	24	27	54	62	91	136	262	367	617	695	256	32
51	36	36	27	36	21	26	23	31	18	24	37	35	44	71	102	154	277	405	621	676	212
52	51	31	45	31	30	32	19	27	29	30	16	18	35	53	80	106	177	245	390	610	596
53	39	30	29	30	30	28	22	29	31	30	49	24	32	45	58	87	137	165	274	419	644
54	36	23	29	25	23	23	24	25	26	25	19	26	24	35	39	58	102	108	188	290	454
55	36	43	30	33	27	23	23	24	29	18	16	3C	25	28	42	51	71	110	143	208	281
56	42	40	29	38	25	28	20	22	29	27	15	22	20	23	26	39	61	67	93	143	223
57	41	34	28	22	33	27	30	14	33	24	26	22	16	28	23	29	57	56	79	108	146
58	45	45	40	29	25	36	28	39	31	27	24	27	23	20	21	28	31	51	62	75	125
59	32	31	29	32	24	36	28	39	30	33	28	25	20	15	22	18	28	42	44	60	80
60	37	42	29	25	39	30	26	26	33	24	30	17	17	16	22	21	21	35	33	56	80
61	47	32	34	33	33	34	28	26	31	19	26	18	21	23	22	22	27	32	31	49	49
62	45	48	44	29	31	31	35	23	30	34	16	24	24	17	13	24	19	24	22	34	41
63	53	45	33	28	38	24	29	26	25	26	27	16	16	25	16	15	13	25	26	33	25
64	40	39	36	36	27	39	25	27	27	11	25	15	14	17	15	18	14	20	23	17	48

Row	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63
1–4																					
5								1													
6–30																					
31	1																				
32–36																					
37	1	1		1																	
38	1																				
39				1	2																
40				1			1	1													
41	2		2		1																
42																					
43		1		1																	
44	1	1		1		1		1							1						
45	3	1		1			1									1					
46		1		1	1										1		1				
47	3		1		1	1	1				1						1	1			
48	4	1		1			1	1	1												
49	7	1	1		1		2	2		1					1				1		
50	6	1	1	4	4	5		1							1				1		
51	20	9	1	3	1	1	1			1				1							
52	156	26	8	3	4	2	4					1			1		1				
53	491	108	12	5	2	1	1	2					1			1					
54	667	465	92	11	2	6	3		1	1		1		1							
55	444	621	413	78	5	4		3	1	1	3										1
56	283	433	622	340	60	10	5	3	1	1			1					1			
57	244	321	496	589	296	54	4	8		4	4			1				1	1		
58	169	250	329	493	532	222	44	7	2		2	1		1	2	1					1
59	115	177	218	329	508	495	216	25	5	3	5	1	1			3	1	1			
60	95	117	152	218	365	432	433	181	32	6	4	2		3	2		1	1			
61	85	120	117	172	210	321	45E	412	154	29	9	3	7								
62	54	87	106	139	160	253	352	479	413	123	18	6	3	1	2		2				
63	45	61	79	117	157	180	255	355	476	323	116	19	2	3	1			1			
64	37	53	70	98	85	147	176	226	342	432	281	110	12	3	2	6	1		1	2	

Figure 3. - Proportional counter data, 5 Ci Pu-Be source.

IDENTIFICATION PULSE HEIGHT

RECOIL ENERGY (keV)		1	2	3	4	5	6	7	8	9	10	11	12	13	14
	1	65536	12636	3177	6369	7665	1236	621	496	2686	155	374	415	510	514
	2	164884	201262	65176	848	231	48	22	37	4	4	4	3	2	9
	3	139285	169469	171244	29673	347	49	9	8	2	3	3	1	1	4
	4	70888	122238	108971	102305	6781	130	36	9	1	1	2	3	1	5
	5	156601	88244	89300	46713	63224	848	68	16	4	2		2	2	1
	6	71376	61879	71858	31277	44332	27938	266	46	5	2	4	1		2
	7	32790	42817	58345	27305	10428	50168	9801	143	13	9	4		2	
	8	14743	28629	47106	24059	9470	7991	44980	3616	33	28	6	4	3	1
	9	7006	18660	38077	21913	9094	3926	11534	36332	1234	55	30	4	5	1
	10	3302	11813	30441	18712	8556	1859	1917	17534	26215	484	40	15	2	1
	11	1661	7668	24472	16482	8343	4133	1815	1356	23483	16466	204	32	14	3
	12	914	4690	18849	14718	7817	4248	1909	951	1754	27929	8143	112	32	9
	13	577	2870	14915	12922	7436	4092	2069	950	658	3791	28118	3262	59	23
	14	345	1818	11949	11494	7192	4040	2046	952	513	458	7987	24347	1321	50
	15	245	1055	9217	10134	6571	3893	2075	1043	497	341	679	12177	17520	145
40	16	167	633	7046	8838	5913	3625	2054	974	523	295	318	1269	17370	11513
	17	123	341	5291	7517	5461	3404	1858	917	461	145	222	334	2336	19782
	18	100	218	3963	6379	4930	3136	1795	940	452	238	174	224	448	4575
	19	65	122	3042	5362	4414	2695	1721	912	447	215	157	149	132	543
	20	67	73	2088	4336	3909	2705	1602	799	419	234	143	138	137	229
	21	59	57	1381	3489	3248	2343	1385	808	400	221	125	106	134	163
	22	41	40	1019	2811	2726	2056	1324	740	402	183	127	88	108	117
	23	63	29	731	2128	2319	1779	1165	671	321	173	115	92	77	113
	24	47	17	403	1602	1918	1540	966	562	315	135	96	73	80	88
	25	30	17	264	1202	1568	1264	828	517	299	125	93	74	74	80
	26	31	18	188	940	1215	1022	766	477	275	129	96	58	53	67
	27	33	15	154	671	970	865	591	383	231	138	87	57	46	64
	28	27	20	87	486	740	662	495	314	186	119	93	62	44	53
	29	41	12	72	323	601	580	404	270	179	113	55	38	47	45
	30	28	8	45	216	442	493	357	277	151	73	63	48	39	48
	31	43	18	28	160	304	348	282	172	130	86	46	48	19	38
	32	25	8	21	118	229	297	266	183	111	83	43	36	56	41
	33	19	13	21	70	174	231	197	154	102	77	54	39	32	30
	34	14	8	21	56	136	156	163	128	74	67	52	37	36	37
	35	21	10	14	42	98	144	151	114	74	67	33	43	30	33
	36	22	13	12	26	83	109	101	104	57	56	41	32	39	25
	37	14	6	12	19	53	73	89	78	67	56	30	32	32	25
	38	20	6	9	14	35	72	69	59	62	39	45	34	30	25
100	39	14	5	7	13	27	48	68	67	43	40	31	29	32	33
	40	20	4	8	10	14	32	62	59	41	37	36	30	26	24
	41	18	10	15	6	12	39	28	62	44	29	36	37	29	26
	42	15	5	9	5	17	27	31	46	47	25	30	30	28	25
	43	14	4	10	5	12	20	20	39	37	33	29	31	28	27
	44	13	7	8	8	6	14	37	30	36	27	34	18	40	24
	45	8	13	4	9	7	8	18	34	35	30	24	34	21	10
	46	7	6	5	5	4	11	23	27	28	31	25	23	28	24
	47	12	4	4	3	8	12	15	20	22	26	25	23	31	24
	48	11	6	7	2	2	6	11	25	23	24	31	28	27	14
	49	8	6	4	2	7	8	10	10	27	22	30	26	25	24
	50	8	7	2	4	3	1	9	12	23	30	28	21	16	25
	51	7	4	8	4	3	4	15	17	21	20	24	24	22	21
	52	6	4	4	2	3	3	6	9	18	21	21	25	26	15
	53	10	3	3	5	1	4	7	13	19	20	15	13	17	25
	54	7	6	5	2	2	1	9	15	18	26	20	24	13	14
	55	5	6	8	5	1	1	3	9	16	20	30	15	20	17
	56	6	4	7			1	3	14	10	19	14	19	25	18
	57	7	7	4	2	2		1	3	18	25	23	22	25	20
	58	8	3		1	1	1	5	11	10	22	21	19	18	25
	59	4	3	2	4	1			5	12	17	22	20	25	26
	60	2	2	5	1	2	3	1	6	16	24	15	24	20	17
	61	1	1	4	7		1		6	6	26	26	22	24	23
	62	1	3	3	6	2	2		4	6	13	26	21	21	23
	63	9	2	6	1			1		12	19	12	24	20	30
165	64	6	1	4	3	1	1		3	5	11	13	16	18	26

	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	524	256	152	118	96	78	82	58	67	35	20	16	14	11
2	6	1		4		2	1	2		1	1			
3	3			1					1		1	1		
4	1	1			1		1							
5						1								
6	1													
7	1	1	1											
8	1			1										
9	1													
10	1													
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12	1	2	1											
13	8	2	2		1									
14	11	3	2											
15	33	6	3											
16	171	27	8	2										
17	5267	46	16	6	2	1								
18	19165	2840	59	19	2	2	1							
19	7341	16831	1063	32	19	2	1							
20	1135	13576	12540	316	17	9	1	1						
21	284	2340	13141	8139	94	15	5	4	1					
22	158	384	3407	14679	4325	52	15	2	4	1		1		
23	141	223	589	5216	14159	1822	32	7	2	2	2	1		
24	126	99	226	1052	7318	11871	630	19	7	4				
25	93	93	137	255	1684	9301	8798	179	12	7	2	1		
26	64	96	116	144	441	2494	10668	5582	65	17	6	1	1	1
27	45	69	92	124	185	688	3325	11136	3239	45	14	5		
28	62	57	86	107	129	252	1030	4508	10394	1553	25	8	2	2
29	42	53	64	76	77	151	346	1480	5677	9248	628	16	7	1
30	52	48	49	63	65	103	148	532	1994	7038	6925	228	15	5
31	45	39	50	45	64	90	96	201	747	2603	7654	4670	77	41
32	32	30	41	50	56	60	83	121	312	1090	3357	8193	2736	39
33	24	39	44	37	52	59	66	75	157	448	1271	4110	7823	1277
34	27	24	45	43	48	58	68	87	117	202	617	1665	4912	6778
35	27	33	34	36	49	40	75	67	96	124	292	773	2070	5614
36	26	16	29	43	42	52	48	61	64	72	153	407	1028	2485
37	32	32	33	31	36	44	46	51	59	71	86	227	531	1248
38	24	29	33	21	31	49	51	49	41	46	80	124	303	657
39	25	33	26	28	38	44	39	48	47	50	70	70	204	391
40	28	23	21	32	28	50	47	36	37	36	60	58	108	222
41	27	24	25	24	26	20	27	33	38	47	48	54	70	151
42	26	19	22	30	27	29	29	43	37	24	27	57	60	78
43	19	22	19	24	31	27	26	28	29	32	39	32	51	76
44	15	25	16	27	24	24	24	36	33	36	32	32	43	51
45	24	18	20	29	21	23	29	24	22	21	26	40	31	37
46	27	22	15	13	25	27	32	33	23	36	36	33	33	38
47	32	27	20	32	19	17	26	23	23	23	26	36	29	29
48	17	16	29	24	22	20	23	20	24	22	35	30	39	29
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50	24	10	25	21	27	26	30	20	22	23	18	30	28	33
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57	19	26	22	20	17	26	15	17	10	16	17	15	19	17
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59	13	25	23	21	17	10	17	11	18	23	13	21	17	16
60	15	16	15	22	14	18	13	13	20	19	21	22	20	21
61	17	26	20	21	22	13	13	16	27	16	15	11	22	18
62	26	19	21	16	15	19	11	17	13	17	14	15	29	23
63	24	22	20	23	14	16	16	19	13	13	20	20	22	19
64	11	14	24	19	21	21	19	20	24	15	22	11	20	22

	29	30	31	32	33	34	35	36	37	38	39	40	41	42
1	5	2	5	8	1	2		1			1	1		1
5	1													
25		1												
29		1												
30	1	1												
31	2	2	1											
32	9	2	1											
33	23	1	5			1	1							
34	445	9	7	6										
35	5315	160	8	7		1								
36	5352	3557	53	9	3	2								
37	2794	6269	2134	32	14	4	1	1						
38	1569	3252	6379	1139	14	4	1	1						
39	836	1747	3574	5346	598	16	1	2	1		1			
40	437	936	1270	3766	4440	224	9	2	2					
41	262	562	1348	2165	4006	3494	89	13	4	1				
42	192	357	544	1258	2293	4297	2493	45	9	2	2			
43	150	205	521	765	1343	2385	4252	1653	25	6	1	2		
44	90	150	261	537	804	1630	2506	3960	978	15	3	4	2	1
45	60	111	179	336	587	859	1636	2549	3735	479	10	2	3	1
46	48	78	135	238	363	625	925	1932	2806	3175	190	8		1
47	35	65	102	139	262	429	739	977	2063	2921	2430	72	2	2
48	38	46	83	136	185	277	441	767	1144	2251	2964	1603	10	4
49	38	45	61	86	149	243	328	498	685	1253	2224	2669	905	17
50	17	37	45	51	94	166	230	347	532	841	1431	2252	2646	447
51	27	25	33	64	79	165	171	273	397	654	791	1726	2312	2231
52	12	34	28	43	76	111	152	229	281	436	695	901	1816	2284
53	23	17	31	36	51	80	134	181	250	365	462	720	948	1966
54	28	25	27	37	56	87	99	133	193	276	318	524	728	1539
55	20	13	33	35	39	61	76	131	156	215	315	351	585	744
56	18	31	15	30	35	52	78	10	141	178	264	328	373	608
57	17	17	23	28	34	46	61	75	98	151	191	249	372	378
58	18	15	20	15	29	39	48	76	85	129	149	180	316	322
59	15	17	16	21	23	32	36	57	95	97	146	161	228	294
60	24	17	19	8	27	26	22	48	60	77	104	160	180	272
61	23	22	22	17	20	30	33	56	59	87	109	137	164	211
62	17	19	18	25	29	31	38	45	53	62	100	116	163	173
63	19	13	15	24	14	21	18	17	47	62	65	102	122	132
64	18	23	16	18	21	29	22	29	59	61	78	63	117	154

	43	44	45	46	47	48	49	50	51	52	53	54	55	56
1		2		1				1						
45	1													
47	1	1												
48	2	1												
49	4	1	1											
50	6	3	1											
51	205	7	4											
52	1793	99	6	2	1									
53	2151	1295	20	5	5									
54	2028	2367	342	15	2			1						
55	1208	1981	1328	528	12	2		1						
56	772	1224	1492	1586	260	5	3	1	1					
57	658	717	1353	1946	1339	163	2	1					1	
58	415	700	739	1415	1555	1132	67	5	1		1			
59	345	466	591	913	1534	1543	898	16	6	1	1			
60	314	321	499	677	312	1595	1369	637	9	1	1			
61	254	291	338	565	538	646	1531	1329	445	10	3		1	
62	193	257	303	345	517	536	961	1562	1150	260	4	1		
63	185	200	281	317	358	587	654	1054	1371	1113	182	6	1	
64	155	175	234	312	267	416	639	553	1150	1217	997	90	4	1

Figure 4. - Proportional counter data, 5 Ci-Pu-Be source moderated by tungsten.

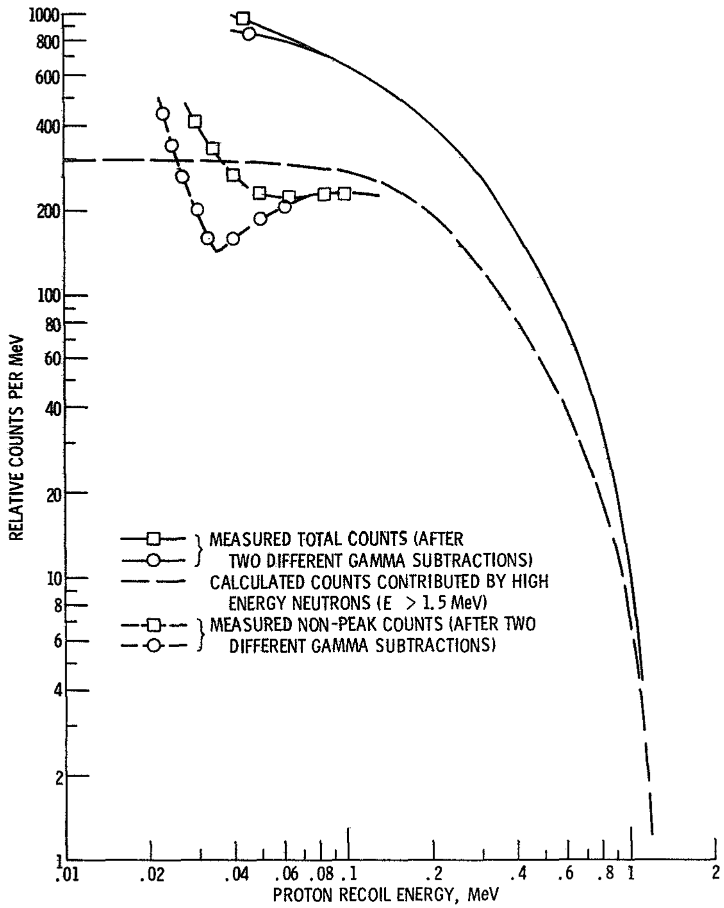

Figure 5. - Comparison of measured with calculated count rates for 5-Ci Pu-Be source.

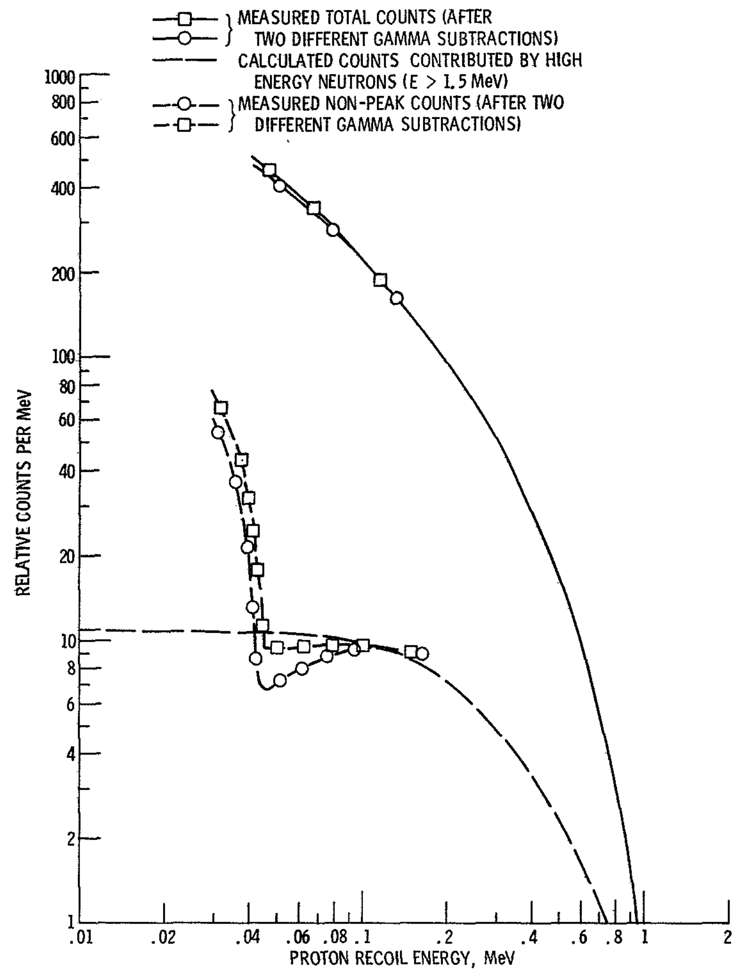

Figure 6. - Comparison of measured and calculated count rates for tungsten leakage flux.

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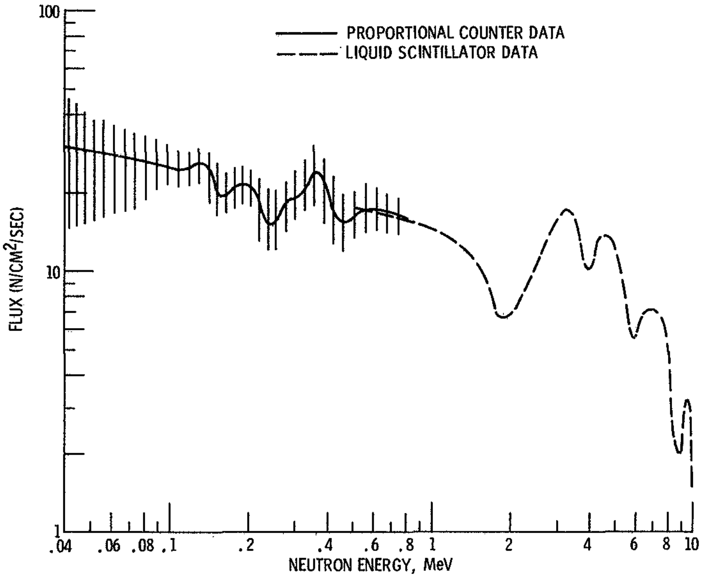

Figure 7. - Neutron flux at one meter from 5 Ci Pu-Be source.

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